

Submitted: 2002 Jun 7

The Spectral Results of the FIRAS Instrument on *COBE*

D. J. Fixsen¹ & J. C. Mather²

ABSTRACT

The Cosmic Microwave Background (CMB) spectral results of the FIRAS instrument are summarized. Some questions that have been raised about the calibration accuracy are also addressed. Finally we comment on the potential for major improvements with new measurement approaches. The measurement of the deviation of the CMB spectrum from a 2.725 ± 0.001 K blackbody form made by the *COBE*-FIRAS could be improved by two orders of magnitude.

Subject headings: cosmic microwave background – cosmology:observations

1. CMB Temperature

The *COBE* (COsmic Background Explorer) satellite was launched on Nov. 18, 1989 (Boggess et al. 1992) with the FIRAS (Far Infrared Absolute Spectrophotometer), DIRBE (Diffuse Infrared Background Experiment) and DMR (Differential Microwave Radiometer) instruments aboard. With 10 months of cold operation and 4 years of total operation the *COBE* provided a new view of the cosmic microwave and infrared radiation. Many papers have been written citing the results of the *COBE* mission, however, many authors have not recognized that the final results of the FIRAS were published in a technically oriented calibration paper (Mather et al. 1999).

The FIRAS data were collected by four detectors operating in three different scan modes. Earlier publications used only the “Left Low Short Slow” and “Right High Short Slow” detector and scan mode combinations. The detectors and modes were checked against each other (Brodde et al. 1997), the DIRBE data (Fixsen et al. 1997b) and the DMR data (Fixsen et al. 1997a) and shown to be consistent with them in the areas of overlap. The final FIRAS “Pass 4” (Brodde et al. 1997) data including all detectors and modes are available from the NSSDC (National Space Science Data Center). The NSSDC also provides detailed explanatory material on the instrument, the data processing, and the calibration model.

¹SSAI NASA/Goddard Space Flight Center e-mail fixsen@stars.gsfc.nasa.gov

²NASA/Goddard Space Flight Center, Infrared Astrophysics Branch

Three independent estimates of the CMB temperature were made from the FIRAS data (Mather et al. 1999). The first uses three thermometers discussed by Fixsen et al. (1994), with a 5 mK readout correction due to the readout current heating the thermometer as discussed by Mather et al. (1999). This approach yields a temperature of 2725.0 ± 1.0 mK with the uncertainty dominated by the absolute calibration of the thermometers.

A second independent temperature estimate relies on the frequencies of galactic CO emission to set the frequency scale and the “color” of the spectrum to determine its temperature, resulting in a temperature of $2725.5 \pm .85$ mK. The uncertainty is dominated by the frequency determination (Fixsen et al. 1996).

A third independent temperature estimate relies on the spectrum of the dipole and its amplitude as determined by the DMR instrument, which was independently calibrated. This results in a temperature estimate of 2722 ± 12 mK (Mather et al. 1999).

The FIRAS measurements indicate that the limits of the Bose-Einstein and Compton distortions are $|\mu| < 9 \times 10^{-5}$ (95% CL) and $|y| < 15 \times 10^{-6}$ (95% CL) (Fixsen et al. 1996). Thus the best result for the FIRAS monopole spectrum is a $2.725 \text{ K} \pm 1 \text{ mK}$ black-body. The measured deviations from this spectrum are 50 ppm (parts per million, root mean square) of the peak brightness of the CMB spectrum, within the uncertainty of the measurement.

It is sometimes stated that this is the most perfect blackbody spectrum ever measured, but the measurement is actually the difference between the sky and the calibrator. It does not determine whether Planck’s formula is correct at the same level of precision. This measurement allows the blackbody spectrum to be different from the Planck function as long as *both* the sky and the calibrator have very nearly the same spectrum. On the other hand, large deviations from the Planck function can be excluded on the basis of the self-consistency of the calibration data alone, which were taken at many different temperatures and frequencies.

Here we recompute the dipole amplitude of the CMB brightness, using the best value of the temperature of 2.725 K. The previous result (Fixsen et al. 1996) used an earlier estimated temperature of 2.728 K. The new result is a dipole amplitude of $(3.381 \pm .007)$ mK or a velocity of 372 ± 1 km/s in the direction $(l, b) = (264.14^\circ \pm 0.15, 48.26^\circ \pm 0.15)$ in close agreement with the DMR result (3.353 mK toward $264.26^\circ, 48.22^\circ$) from Bennett et al. (1996).

2. CALIBRATION

There are several papers (Giorgi 1995, Battistelli et al. 2000, Salvatera & Burigana 2002) that question the FIRAS calibration. Here we address these calibration issues. The FIRAS instrument (Mather et al. 1990) covers the wavelength range from $100 \mu\text{m}$ to 1 cm, with reduced efficiency at short wavelengths. The maximum path difference of 58.5 mm yields an apodized spectral resolution of 0.4538 cm^{-1} . The FIRAS is a differential instrument, with two nearly equivalent

input ports and two output ports. It has two frequency ranges ($1 - 20 \text{ cm}^{-1}$ and $20 - 100 \text{ cm}^{-1}$). Its four semiconductor bolometer detectors are measured with DC current bias and JFET preamplifiers, with sensitivities of the order of a few times $10^{-15} \text{ W/Hz}^{1/2}$.

The calibration was treated thoroughly by Fixsen et al. (1994). To address the questions that have been raised, we summarize only a few key aspects of the calibration. The fundamental measurement is the comparison of the sky with an ideal movable external blackbody calibrator (XCAL) that can fill the aperture of the sky horn. The rest of the calibration process is used to measure key gains and offsets that apply if the calibrator spectrum does not match the sky spectrum.

A second key idea is that a Kirchhoff condition applies to the measured étendues, where an étendue is defined as an effective area-solid angle product coupling a radiation source to a detector. FIRAS detects only modulated signals, but these can have either positive or negative signs. The Kirchhoff condition requires that the sum of all the effective étendues is zero, in our notation, $\sum_k a_{fk} = 0$. This condition is the mathematical statement that the radiation falling on each detector comes from somewhere and, since the detector remains unchanged, for any source eclipsed by the movement of the mirror transport mechanism, there is another source (or sources) that is uncovered by the same motion.

The two intended sources are the internal calibrator (ICAL) and the XCAL. Other sources considered are the sky horn, the reference horn, the moving dihedral mirrors (which modulate the interferometer path difference), the physical support structure, and the bolometer itself. The calibration model explicitly took these seven sources into account, and derived their optical parameters a_{fk} from observations taken with many different combinations of temperatures from 2 to 20 K. The calibration model accounts for almost all of the changes in the interferograms as the calibrators and horns are heated individually and together.

The determination of the effective étendue of the physical structure and the bolometer relies on uncontrolled small variations in the temperature of each. Since both the bolometer and the structure remained below $\sim 2 \text{ K}$ the determination of these elements' effective étendues is unreliable at high frequency, but for the same reason it is not required (their emission at high frequencies is negligible).

Giorgi (1995) suggested there might be an asymmetry of 5% in the two input arms of the FIRAS, although the measured asymmetry is only 1-3% (depending on the frequency) referred to the XCAL. It was measured to $\sim .01\%$ precision by the calibration process, and radiation (or lack thereof) from the bolometer itself makes up most of the difference. In any case this number does not enter the calculation of the accuracy of the XCAL, since the ultimate accuracy depends only on matching the XCAL to the sky.

The FIRAS is absolutely calibrated by its external blackbody. If the spectrum of the sky can be duplicated when the XCAL is inserted in the horn at some temperature, then the sky has the same spectrum as the XCAL. The ICAL, the other parts, and the instrument calibration model

merely serve as an elaborate transfer standard.

Thus two questions are of paramount importance. First, what is the temperature of the XCAL and how well is it known? And second, how close is the spectrum of the XCAL to a blackbody?

To address the first question, the temperature of the XCAL was measured and controlled with four germanium resistance thermometers (GRTs) attached to the XCAL. The XCAL itself was designed to be isothermal (Mather et al. 1999), as there was no known source of significant heat flow through it. The GRTs were carefully calibrated against a National Institute of Standards and Technology standard to 1 mK accuracy. As a further check 10 of the GRTs calibrated in the same batch as the flight GRTs were recalibrated 1.7 yr after launch (Mather et al. 1999).

Three of the thermometers were read out continuously during the 10 month flight while the fourth was used in a feedback circuit to control the temperature. All of the calculations and data indicate that the XCAL was isothermal to $\sim 10 \mu\text{K}$ and the temperature (after corrections) was known to 1 mK. The temperature itself was confirmed by the self-consistency of the calibration model, as described above, using the spectrometer to measure a color temperature based on the dependence of brightness on wavelength.

To address the second question, the XCAL is designed in the shape of a trumpet mute, to allow multiple reflections on the Eccosorb surface to increase its apparent emissivity. Halpern et al. (1986) made careful measurements of the reflection of Eccosorb at various frequencies, and these were used to predict the emissivity of the calibrator. The groove angle of 25° requires that a ray entering the calibrator parallel to the axis will be specularly reflected from the Eccosorb surface 7 times before escape, and moreover will return at an angle of 5° off axis, which is outside the acceptance angle of the horn.

The XCAL is part of a closed cavity composed of the calibrator, the sky horn, a small gap between the calibrator and the sky, and a small aperture leading to the spectrometer horn. Consequently, the radiation reflected by the calibrator must have originated either from itself, the sky horn, the sky itself through the gap, or the small aperture to the spectrometer. The effective emittance of the horn was deduced to be 0.03 from the calibration model. Moreover, since the horn was set to match the temperature of the calibrator, the only source of radiation that could be reflected by the calibrator and was not originally at the calibrator temperature is the small aperture leading to the spectrometer. The reflectance for radiation originating there is the only one that can produce an error in the blackbody spectrum of the calibrator.

Salvatera & Burigana (2002) used the reflectance of the Eccosorb and an approach to physical optics to estimate a raw emissivity of .998 for the XCAL at long wavelengths. We also did a physical optics calculation, finding that the long wavelength reflectance of the calibrator is due almost exclusively to scattering at the edge where it meets the horn. In our opinion the Salvatera & Burigana result must originate from the same location. The next step is to consider the origin of the 0.2% of the radiation that is reflected. As noted above, the cavity has four sources of radiation, only one of which is not at the sky temperature. A short calculation gives an

approximate answer that, if 0.2% is reflected from the XCAL, the reflected radiation is dominated by emission from the XCAL which has bounced off of the sky horn and then reflected off of the XCAL (the sky horn reflectance in this range is .97). This increases the calculated effective emissivity of the XCAL to .99994 or a reflection of 6×10^{-5} . Salvatera & Burigana did not discuss this effect and drew an unnecessarily pessimistic conclusion.

More significantly, rather than depending on complex calculations, direct measurements were made of the reflection of a duplicate of the XCAL (the flight spare) in a duplicate of the sky horn (the flight spare). Measurements were made for a variety of tilts of the XCAL and for frequencies of 30 to 37 GHz and 93.6 GHz (Mather et al. 1999). The largest reflection coefficient observed was 4×10^{-5} (at 35.25 and 36.86 GHz with the XCAL flat). Since the reflection for the FIRAS is averaged over wide frequency bands and many modes the effective reflection is likely to be in the $\text{few} \times 10^{-6}$ range, which was the typical measured reflection. To be conservative we use a limit of 3×10^{-5} .

3. FUTURE MEASUREMENTS

3.1. Motivation

With the improvements listed in §3.2, we think that it should be quite feasible to measure the deviation of the CMB spectrum from a perfect blackbody form with an accuracy and precision of a part per million. Such an instrument could measure or provide upper limits on the cosmic y and μ parameters at the $\sim 10^{-7}$ level, and provide a spectrum of the anisotropy to 10%.

There are many possible causes of distorted cosmic background spectra (Tegmark & Silk 1995). The more radical ideas have already been ruled out by the FIRAS data, but attenuated versions of them may still be viable. These include: 1. The dissipation of gravity waves, turbulent energy, or inhomogeneity in the early universe. While inflationary predictions are in good agreement with the anisotropy and spectrum observations, small but uniform additions to the energy of the CMB field might still be hidden from us. The behavior of the dark matter as it clumps might not be so innocent as is generally assumed. 2. Slight non-equilibrium behavior at the decoupling, due to the optical thickness of the Lyman alpha line, or the presence of small concentrations of LiH or H_2D^+ molecules (Dubrovich & Lipovka 1994). 3. The decay of unstable particles, or the conversion of dark matter particles or energy to ordinary energy. There is so far no reason to expect them but the work of elementary particle physics is still not finished. 4. The unknown effects of dark energy or quintessence fields. 5. The general Sunyaev-Zeldovitch effect, accumulated from all the galaxy clusters and hot intergalactic medium (Ceballos & Barcons 1994). 6. The effects of re-ionization, perhaps at a redshift of 6 to 30 (Yamada & Fujita 2001). 7. Unexpectedly dusty early galaxies, with dust barely above the blueshifted CMBR temperature of 2.7 (1 + z) K (Aghanim et al. 2000).

The understanding of the foreground emission from the Galactic dust might have limited the FIRAS accuracy at a level only a little below the noise level we reported before. However, an improved instrument would provide much better sensitivity to these foregrounds with much better angular resolution, so we think that the foregrounds would allow at least two orders of magnitude improvement on the cosmic distortion parameters. For instance, detailed observation of the Galactic lines allows a way to separate local emission from that at significant red-shifts.

In the process, the improved instrument would also provide maps of many components of the interstellar medium: dust of several types and temperatures could be recognized, the atomic and molecular lines could be mapped with great precision, and at long wavelengths the contribution of galactic synchrotron and free-free emission might be directly detectable even at the relatively short wavelengths of an infrared instrument. Improved sensitivity, combined with the ability to point the instrument at selected objects, would also permit concentrated observations of external galaxies and galaxy clusters (Colafrancesco et al. 1997). As the spectra and spatial distributions of these foregrounds objects are quite different over the wide spectral range of the FIRAS, it would be possible to separate their contributions in data analysis, leading to a precisely measured residual cosmic background radiation spectrum.

Improved sensitivity might allow detection of the metals from population III stars (Rowan-Robinson et al. 1979).

3.2. Technical Approach

Technology has improved immensely since the *COBE* mission was conceived in 1974. Infrared detectors are 1000 times more sensitive, and are now available in arrays. Deep space environments like the Sun-Earth Lagrange point L_2 are routinely planned for missions that would be adversely affected by proximity to the Earth. It has also been recognized that instruments are no longer limited to the size of their cryostats, if they can be cooled after launch. Microwave technology has also improved, leading to plans for precise measurement of the CMB temperature at wavelengths out to 30 cm (Kogut 1996).

Thus one can contemplate what a new version of the FIRAS might look like. First, new bolometric detectors would achieve much higher sensitivity. The FIRAS detectors were limited both by their own internal noise and by cosmic ray impacts. A new detector would have a much smaller cross section and so have a much lower cosmic ray impact rate. Also, a much more sensitive detector allows more effective detection of the few remaining cosmic rays. We still recommend the choice of a Michelson interferometric spectrometer, for many reasons relating to its differential nature, its ability to handle large étendues, and the operator's control of the spectral response function. We would consider pointing horns at a large parabolic reflector to obtain a much smaller beamwidth, but this requires careful analysis of the effects of beam spillover, and excellent control of stray light from any warm parts of the observatory. Although

not strictly required for the spectrum measurement, a smaller beam on the sky allows more pixels to compare for galactic radiation removal, reduce the fraction of the sky seriously contaminated by galactic radiation, and add valuable information about the galaxy and the anisotropy. Finally, by operating at the L_2 point of the Earth-Sun system, the instrument needs much less shielding from the Earth.

We would explore the design of a beam-forming optical system to replace the parabolic horn. This was considered at the beginning of the COBE project but no solution was found within the volume constraints of the interior of the cryostat. Now that deep space missions can be flown with much larger cold instruments located far from warm objects, a more traditional optical imaging system could be made, using standard coronagraphic techniques of Lyot stops to trim diffraction sidelobes. Such a system would allow the use of detector arrays instead of single detectors, for better angular resolution. It could also eliminate most of the "Narcissus effect" suffered by the FIRAS. This effect is caused by light reflected from the detectors, returning to the input concentrator, and being partially reflected to make another pass into the spectrometer. In the FIRAS this effect causes spurious responses that simulate harmonics of the input frequencies (Brodde et al. 1997), although it does not prevent an accurate differential comparison of a blackbody with the sky.

To calibrate such a system would still require a complete measurement of all radiation that could enter the instrument, so a large closed structure to emulate the FIRAS calibrator - horn combination would be required. For example, we would surround the entire optical system with segmented blackbody radiators to measure the sidelobe responses and ensure that the source of every photon is understood. While large and awkward, such a calibration system is not infeasible and could still reach extreme accuracy through control of all temperature gradients.

Modern interferometer designs include several ways to make the instrument nearly immune to alignment errors, using cube corners or other retro-reflectors instead of the dihedral mirrors that FIRAS used to rotate the polarization state. Modern designs also use focusing optics to reduce the size of the beamsplitters to a much more manageable size. Both of these improvements would enable superior optical performance for the interferometer.

We leave open the question of wavelength range. The FIRAS wavelength range was limited by its étendue to $\lambda < 1$ cm. It might be possible to use microwave technology with the same or similar calibrators used by the new FIRAS to enable an extension of precise spectrophotometry with a common thermometric scale all the way out to 10 cm, but the size of the calibrator and horns grows with wavelength and at some point becomes impractical.

The calibration accuracy could be improved by different choices in the calibrator design. In the case of FIRAS, there was a significant concern about heat from the spacecraft's sunshield that might impinge on the calibrator support arm, necessitating a different thermal design for the calibrator itself. There was also concern that some of this heat might bounce off the support arm and through the gap between calibrator and horn, although there was no evidence of such a path

in the flight data.

The largest uncontrolled and imperfectly measured effect that limited the FIRAS calibration accuracy was the calibrator reflectance of light that originated (or failed to originate) in the instrument volume, and was transmitted up the sky horn toward the calibrator. Our calculations showed that most of this reflectance is due to diffraction at the junction between the calibrator and the horn. With a new design it would be possible to make this occur at a spot that is not visible to the detectors, attenuating the error by orders of magnitude. This effect could be measured directly with shutters and heated blackbodies and beamsplitters shining radiation up towards the calibrator. It could also be largely eliminated by heating the instrument chamber, with all its optics and support structures, to the same temperature as the calibrator and horn. Only the detectors need to be at temperatures different from 2.725 K. To measure the radiation originating at the detectors, one of the detectors could be heated to detect its effect on the other detector, and vice versa. This effect was too small to measure in the FIRAS data.

We recommend that a future instrument be built in a completely symmetrical way. The next generation instrument should have two identical inputs, each with its own movable external calibrator and sky horn. To fully utilize the symmetry, 1/4 of the data should be taken in each of 4 modes: both calibrators in, both out, one in, and the other one in. This allows checking the calibrators against each other as well as against the sky, and enables an end-to-end system calibration and performance test before launch, something that was not possible for the FIRAS.

Improved detector characterization is also possible. The FIRAS took data in only one direction of the stroke, but to fully characterize the detectors data should be taken in both directions of the scan. With computer control the scan length could be varied from scan to scan, enabling a search for any errors that relate to the exact length of stroke. This would also allow for the necessary apodization to happen at the data collection time, optimizing the observing efficiency. An apodized symmetric scan pattern would allow systematic detection and correction at a deeper level into the already lower noise of the detectors.

In the case of the FIRAS, only 10% of the total observing time was devoted to calibration data. This choice limited the calibration accuracy because detector noise was the dominant limiting factor. With new detectors, it might be possible to reach the systematic error limits much more quickly. Ideally these limits would also be reduced by better calibration design.

4. ACKNOWLEDGEMENTS

The *COBE* mission was steadily supported by NASA Headquarters from 1976 through launch in 1989 and 7 years of data analysis. Scientific guidance was provided by the Science Working Group, and the mission was designed and constructed at Goddard Space Flight Center.

REFERENCES

- Aghanim N., Balland C. & Silk J., 2000, *A&A*, 357, 1
- Battistelli, E.S., Fulcoli, V., & Macculi, C., 2000, *New Astronomy*, 5, 77
- Bennett, C.L., et al. , 1996, *ApJ*, 464, L1
- Boggess, N.W., et al. , 1992 *ApJ*, 397, 420
- Brodd, S., Fixsen, D. J., Jensen, K. A., Mather, J. C. & Shafer, R. A., eds 1997, *COBE FIRAS Explanatory Supplement*, COBE Ref. Pub. No. 97-C (Greenbelt, MD: NASA/GSFC), available in electronic form from the NSSDC.
- Ceballos M.T. & Barcons X., 1994, *Mon Not R Astron Soc*, 271, 817
- Colafrancesco S., Mazzotta P., Rephaeli Y. & Vittorio N., 1997, *ApJ*, 479, 1
- Dubrovich V.K., & Lipovka A.A., 1994, *A&A*, 296, 301
- Fixsen, D.J. et al. , 1994, *ApJ*, 420, 445
- Fixsen, D.J. et al. , 1996, *ApJ*, 473, 576
- Fixsen, D.J. et al. , 1997a, *ApJ*, 486, 623
- Fixsen, D.J. et al. , 1997b, *ApJ*, 490, 482
- Giorgi, P.G., 1995, *Infrared Physics Tech.*, 36, 749
- Halpern, M., et al. , 1986, *Appl. Opt*, 25, (4) 565
- Kogut, A., 1996, *astro-ph/9607100*
- Mather, J. C. et al. , 1990, *ApJ*, 354, L37 .
- Mather, J. C. et al. , 1999, *ApJ*, 512, 511
- Rowan-Robinson, M., Negroponte J., & Silk J. *Nature*, 281, 635
- Salvatera, R. & Burigana, C. 2002 *Mon Not R Ast S* (Submitted) *astro-ph 0203294*
- Tegmark M. & Silk J., 1995, *ApJ*, 441, 458
- Yamada M. & Fujita Y., 2001, *ApJ*, 553, L145